

A COMPREHENSIVE FRAMEWORK FOR PRIORITIZING FUEL ALTERNATIVES IN SUSTAINABLE MARITIME TRANSPORT USING INTEGRATED AHP-VIKOR METHODS

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ABSTRACT

Maritime transportation enables the movement of large quantities of goods across the globe at low costs. A significant portion of global trade takes place through sea routes. Therefore, maritime transportation holds an important place in the global economy. However, the extensive use of traditional fossil fuels in the maritime sector leads to the emission of harmful substances such as carbon dioxide (CO₂), nitrogen oxides (NO_x), and sulfur oxides (SO_x), posing risks to human health and marine ecosystems. To minimize these effects, the maritime sector needs a sustainable transformation. International regulations, the limited availability of fossil fuels, high fuel costs, and societal pressures have further accelerated the shift toward alternative fuels. In this regard, this study evaluates marine fuel alternatives, including heavy fuel oil (HFO), marine diesel oil (MDO), liquefied natural gas (LNG), liquefied petroleum gas (LPG), electricity, hydrogen, methanol, and ammonia, for sustainable maritime transport by using an integrated AHP and VIKOR method. In the first stage, the criteria of carbon emission, energy efficiency, cost, supply accessibility, safety, and infrastructure were identified through a literature review and expert opinions. Subsequently, their relative importance was calculated using the AHP method, and finally, the VIKOR method was used to rank the fuel alternatives. According to the results, electricity was identified as the most suitable alternative for achieving sustainability in the maritime sector because of its high energy efficiency, low carbon emissions, and ease of maintenance. Hydrogen, methanol, and

ammonia, which offer low or zero carbon emission potential depending on their production pathways, were considered among the alternative fuels suitable for long-term evaluation. Alternative fuels play a prominent role in sustainable maritime transportation because they reduce environmental impacts, enhance energy efficiency, and deliver enduring economic benefits. This study contributes to promoting sustainability in the maritime sector.

Keywords: sustainable maritime transportation; marine fuels; AHP; VIKOR

1. Introduction

Maritime transport, accounting for a large portion of global trade, holds a significant place in the world economy. Due to its low unit transport costs, large cargo capacity, and international accessibility, maritime transport is an indispensable part of global logistics chains. However, despite all its economic advantages, the maritime sector faces the need for a significant transformation in terms of sustainability due to its negative environmental impacts (Xiao et al., 2024). Fossil fuel-based traditional maritime activities cause severe damage to both the atmosphere and the marine ecosystem through greenhouse gas emissions, acidic pollutants (NO_x, SO_x), and particulate matter (Serra & Fancello, 2020; Y. Wang & Wright, 2021). Therefore, the growing awareness of climate change and the pressure of international regulations have increased the necessity of adopting cleaner energy sources in the maritime sector. In this context, the International Maritime Organization (IMO) has developed a strategic plan aiming to reduce sectoral greenhouse gas emissions by at least 50% by 2050 (IMO, 2018; Joung et al., 2020). This policy supports the adoption of cleaner energy sources and encourages the shift towards alternative fuels in the sector. Among alternative fuels, liquefied natural gas (LNG), liquefied petroleum gas (LPG), methanol, ammonia, hydrogen, biofuels, and electricity stand out with their potential to reduce carbon footprints and relatively low environmental impacts. Nevertheless, each alternative fuel has both advantages and challenges in terms of cost, storage, and safety. For example, hydrogen, despite its zero-carbon emissions potential, faces various technical barriers due to storage difficulties and safety risks (Wang & Wright, 2021). LNG, while compatible with the existing infrastructure and offering a practical solution for the transition period, presents uncertainties regarding its alignment with long-term climate targets due to methane leakage and total life cycle emissions (Serra & Fancello, 2020). Hence, the maritime industry requires a comprehensive evaluation that addresses environmental, economic, technical, and operational criteria rather than evaluating fuel alternatives based on a single performance criterion (Kim et al., 2020).

While the environmental impacts of fossil fuels have been widely studied in the literature, the systematic evaluation of alternative fuels from a sustainability aspect using Multi-Criteria Decision-Making (MCDM) methods is limited. To fill this gap, therefore, this study presents a multi-dimensional decision model that evaluates sustainable fuel alternatives in maritime transport. The main purpose of the study is to support the transition toward cleaner energy use in the maritime sector by identifying the most sustainable fuel options based on a set of comprehensive criteria. Sustainability is not only limited to environmental impacts. It also encompasses important factors such as economic costs, supply chain continuity, infrastructure requirements, and societal acceptance (Strantzali et al., 2023). For this reason, a systematic evaluation is required to determine the relative importance of these factors and compare fuel alternatives. In this regard, the relative importance levels of criteria were determined using the Analytic Hierarchy Process (AHP) method,

and fuel alternatives were ranked using the *VlseKriterijumska Optimizacija I Kompromisno Resenje* (VIKOR) method. The AHP method enables a consistent weighting of criteria based on expert judgment, while the VIKOR method identifies compromise solutions by balancing conflicting objectives (Soner et al., 2017). The integrated AHP-VIKOR approach enables the systematic weighting of decision criteria and a balanced, consensus-based evaluation among fuel alternatives. According to the findings, carbon emission emerges as the most prioritized criterion, followed by cost and safety. These results highlight that environmental and economic considerations play decisive roles in sustainability-oriented fuel assessments. Among the evaluated alternatives, electricity ranks as the most sustainable option, followed by hydrogen and methanol. These findings are consistent with global decarbonization goals and highlight the increasing potential of renewable-based fuels in the maritime sector.

The originality of this study lies in its comprehensive approach, where environmental, economic, and technical aspects are jointly evaluated to determine suitable fuel alternatives for sustainable maritime transport. The proposed methodology integrates the AHP and VIKOR methods, thereby ensuring more accurate and consistent results throughout the evaluation process. This integrated structure strengthens the methodological design of the study and offers practical insights. It helps identify fuel alternatives that align with international decarbonization goals and supports policy efforts to accelerate the sector's transition toward cleaner energy. Overall, the study contributes to the literature by offering a transparent and systematic basis for sustainability-oriented fuel evaluation in maritime transport. The results reveal fuel alternatives that can contribute to a cleaner and more sustainable future for the maritime sector.

2. Literature review

A literature review was conducted through the Scopus database using a set of predefined keywords “maritime transport” AND “MCDM”, “maritime transport” AND “AHP”, “maritime transport” AND “fuel” AND “decision making”, “maritime transport” AND “fuel alternatives” AND “decision making”, “maritime transport” AND “fuel” AND “MCDM”, and “marine fuels” AND “MCDM”. The studies that apply MCDM methods and are relevant to this research were identified through this search and are summarized in Table 1. In addition to these studies, the search also revealed several related works that do not employ MCDM methods. These include research examining the environmental and sustainability aspects of alternative marine fuels (Al-Enazi et al., 2022; Foretich et al., 2021; Law et al., 2021; Tomos et al., 2024; Y. Wang & Wright, 2021), assessing their economic feasibility and cost implications (Mukherjee et al., 2023), and exploring the potential of various biofuels (Kesieme et al., 2019; Raslavičius et al., 2014; Rony et al., 2023). Overall, the literature indicates that the number of studies that use MCDM methods in maritime transport and integrate these methods is limited. MCDM methods are effective tools, especially for complex decision-making processes, such as evaluating fuel alternatives and determining sustainable solutions.

Table 1
MCDM-based studies on marine fuel alternatives

Year	Authors	Aim	Methods
2025	Sevim and Zincir	Selection of the optimum sustainable maritime biofuel	AHP
2024	Ebadi Torkayesh et al.	Analysis of market development barriers for renewable fuels in the German transport sector	DEMATEL
2023	Strantzali et al.	Evaluation of alternative maritime fuels	PROMETHEE II
2023	Yang et al.	Assessing alternative low-carbon fuel technologies	AHP
2023	Moshiul et al.	Selection of alternative fuel for decarbonizing maritime deep-sea shipping	TOPSIS
2023	Soltani Motlagh et al.	Selection of sustainable decarbonization options for container shipping	AHP, TOPSIS
2021	Mandić et al.	Evaluation of alternative marine fuels for sustainable coastal marine traffic	AHP, SAW
2021	Andra Luciana et al.	Comparison of LNG and oil-gas as alternative marine fuels	AHP
2019	Hansson et al.	Assessment of alternative marine fuels involving Swedish stakeholders	AHP
2017	Ren & Lützen	Selection of sustainable alternative energy sources for shipping	AHP
2016	Deniz & Zincir	Assessment of alternative fuels for ships	AHP
2015	Ren & Lützen	Selection of technology for emissions reduction in shipping	AHP, VIKOR

AHP: Analytics Hierarchy Process, DEMATEL: DEcision MAKing Trial and Evaluation Laboratory, PROMETHEE II: Preference Ranking Organization METHod for Enrichment Evaluations II, SAW: Simple Additive Weighting, TOPSIS: Technique for Order Preference by Similarity to Ideal Solution, VIKOR: VlseKriterijumska Interaktivna Kompromisno Odločanje Ranking

3. Methodology

MCDM methods are crucial tools in decision-making processes that involve complex and multiple criteria. These methods enable decision-makers to evaluate different alternatives based on various criteria and identify the most optimal solution (Sahoo & Goswami, 2023). In this study, the fuel types used in maritime transport were assessed within a sustainability framework using integrated AHP-VIKOR methods. The AHP method was developed to structure complex decision problems hierarchically and to determine the priorities among the criteria (Saaty, 1980; Saaty & Vargas, 2012). In contrast, the VIKOR method ranks alternatives in a compromise manner based on the defined criteria (Opricovic & Tzeng, 2004). The AHP and VIKOR methods are considered

important tools in decision-making processes, and due to the systematic evaluation opportunities, they provide to decision-makers, they are widely used in various applications in the literature. The proposed methodology is shown in Figure 1.

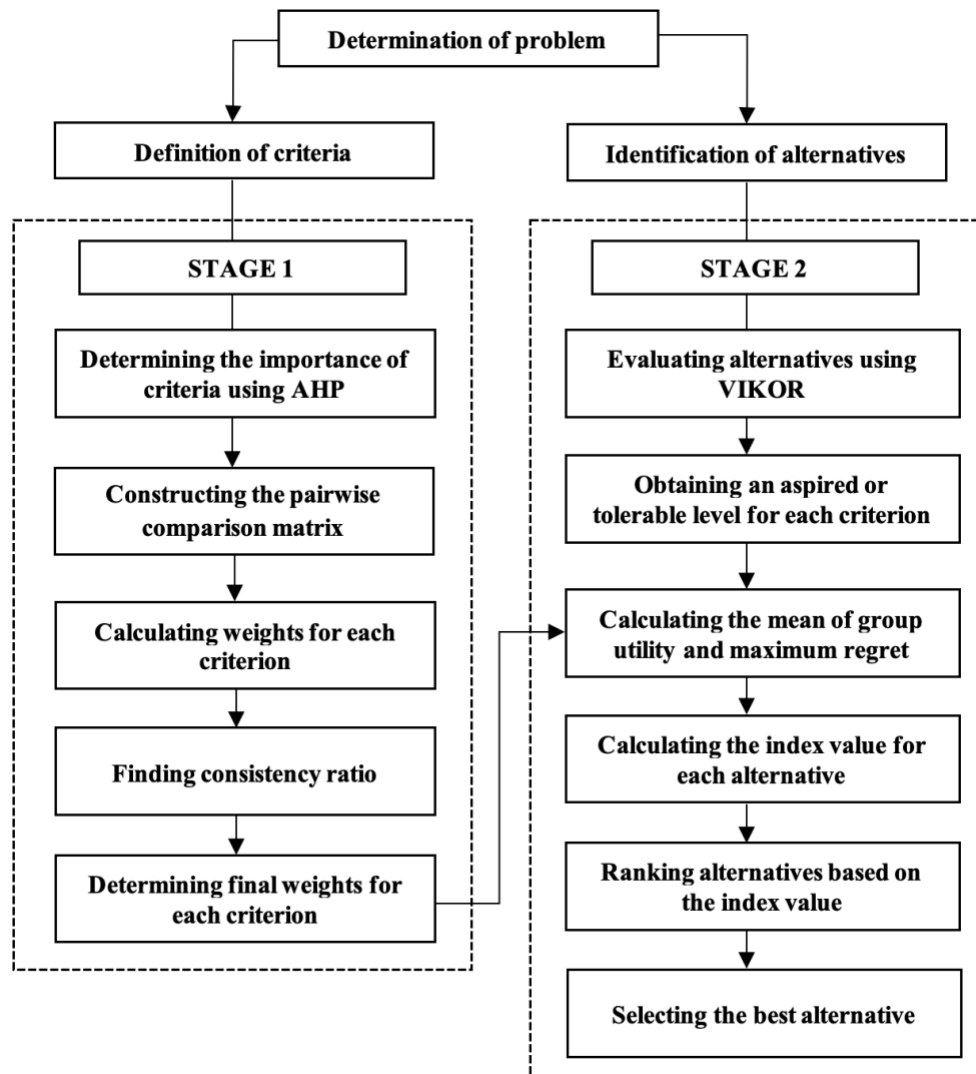


Figure 1 Proposed methodology

3.1 AHP method

The AHP method is widely used in decision-making and problem-solving processes (Saaty, 1980). It is an effective tool for addressing complex, multi-criteria decision problems. One of its key strengths is providing decision-makers with an intuitive and logical framework, which simplifies and clarifies the decision-making process (Saaty & Vargas, 2012).

The steps of the AHP method are outlined below (Saaty, 1980, 2008; Saaty & Vargas, 2012):

Step 1: In order to ensure a systematic and consistent progression of the decision-making process, the problem is first structured hierarchically, with the goal, criteria, and alternatives clearly defined.

Step 2: Pairwise comparison matrices are created using the evaluation scale given in Table 2 by the decision-makers, as shown in Equation (1).

Table 2
Pairwise comparison scale

Intensity	Definition of importance
1	Equal importance
3	Moderate importance
5	Strong importance
7	Very strong importance
9	Extreme importance
2, 4, 6, 8	Intermediate values

Let us assume that there are n criteria at the same level, which are conflicting with each other. a_{ij} represents the relative importance of the i th criterion in comparison to the j th criterion.

$$A_{n \times n} = \begin{bmatrix} 1 & a_{12} & \dots & a_{1n} \\ 1/a_{12} & 1 & \dots & a_{2n} \\ \vdots & \vdots & & \vdots \\ \vdots & \vdots & & \vdots \\ 1/a_{1n} & 1/a_{2n} & \dots & 1 \end{bmatrix} \quad (1)$$

Step 3: The eigenvector representing the importance of each criterion relative to the others in the pairwise comparison matrix is calculated using Equation (2) and Equation (3).

Let $i = 1, 2, \dots, n$ and $j = 1, 2, \dots, n$;

$$b_{ij} = \frac{a_{ij}}{\sum_{i=1}^n a_{ij}} \quad (2)$$

$$w_i = \frac{\sum_{j=1}^n b_{ij}}{n} \quad (3)$$

A column vector W is formed to determine the relative importance weights of the criteria, as shown in Equation (4).

$$W = \begin{bmatrix} w_1 \\ w_2 \\ \vdots \\ \vdots \\ w_n \end{bmatrix} \quad (4)$$

Step 4: The consistency ratio (CR) of the pairwise comparison matrix is calculated to analyze whether any inconsistency exists in the decision-makers' evaluations. This ratio indicates the degree of consistency in the comparisons, with an acceptable upper limit of 0.10. If the CR value exceeds 0.10, the relevant comparisons must be reviewed and reassessed. The CR is determined by Equation (5), and the λ_{max} value used in this calculation corresponds to the largest eigenvector of the comparison matrix. The random consistency index (RI) is given in Table 3 based on the number of criteria.

$$CR = \frac{CI}{RI} \tag{5}$$

$$CI = \frac{\lambda_{max} - n}{(n - 1)} \tag{6}$$

Table 3
Random consistency index (RI)

n	1	2	3	4	5	6	7	8	9	10
RI	0.00	0.00	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49

3.2 VIKOR method

The VIKOR method was developed to rank solution alternatives and determine the best solution for complex problems. The method focuses on providing a “compromise solution” in situations where conflicting criteria exist. A compromise solution refers to an alternative that achieves a reasonable balance among all criteria, representing the most acceptable option for decision makers under trade-off conditions. The foundation of the VIKOR method is based on the following L_p criterion (Opricovic & Tzeng, 2004).

The VIKOR method $L_i^{p=1}$ (as S_i) and $L_i^{p=\infty}$ (as R_i) are used to formulate ranking measure.

$$L_i^p = \left\{ \left[\sum_{j=1}^n w_j (|f_j^* - f_{ij}|) / (f_j^* - f_j^-) \right]^p \right\}^{1/p} \quad 1 \leq p \leq \infty \tag{7}$$

The steps of the VIKOR method are as follows (Opricovic ve Tzeng 2004):

Step 1: The best f_j^* and the worst f_j^- values are calculated for each criterion $j = 1, 2, \dots, n$. Assume that j th function in Equation (8) denotes benefit criterion and j th function in Eq. (9) denotes cost criterion:

$$f_j^* = \max_i x_{ij}, f_j^- = \min_i x_{ij} \tag{8}$$

$$f_j^* = \min_i x_{ij}, f_j^- = \max_i x_{ij} \quad (9)$$

Step 2: The values of S_i and R_i are calculated for each alternative. S_i and R_i represent the mean of group utility and the maximal regret value, respectively.

$$S_i = \sum_{j=1}^n w_j (f_j^* - x_{ij}) / (f_j^* - f_j^-) \quad (10)$$

$$R_i = \max_j [w_j (f_j^* - x_{ij}) / (f_j^* - f_j^-)] \quad (11)$$

Step 3: The Q_i index value is calculated for each alternative.

$$Q_i = v \frac{(S_i - S^*)}{(S^- - S^*)} + (1 - v) \frac{(R_i - R^*)}{(R^- - R^*)} \quad (12)$$

where $S^* = \min_i S_i$, $S^- = \max_i S_i$, $R^* = \min_i R_i$, $R^- = \max_i R_i$ and v is introduced as the weight for the strategy of “maximum group utility”, whereas $(1 - v)$ is the weight of the individual regret of the “opponent”.

Step 4: Sort the alternatives by the value of S_i , R_i ve Q_i in descending order. Propose the alternative $A^{(1)}$ as a compromise solution which is arranged by the measure $\min Q_i$ if the two conditions are satisfied:

C1. Acceptable advantage:

$$Q(a^{(m)}) - Q(a^{(1)}) \geq 1/(m - 1) \quad (13)$$

where, m refers to the number of alternatives and $A^{(2)}$ is the second position among the alternatives ranked by Q_i .

C2. Acceptable stability in decision making: Alternative $A^{(1)}$ must also be the best ranked by S_i or/and R_i .

If one of the conditions is not satisfied, then a set of compromise solutions is proposed, which consists of:

- Alternatives $A^{(1)}$ and $A^{(2)}$ if only C2 is not satisfied, or
- Alternatives $A^{(1)}$, $A^{(2)}$, . . . , $A^{(M)}$ if C1 not satisfied; $A^{(M)}$ is determined by the relation $Q(A^{(M)}) - Q(A^{(1)}) < D(Q)$ for maximum M (the positions of these alternatives are close).

4. Application

In this study, marine fuels were compared using MCDM methods with a sustainability-focused approach. For this purpose, the relative importance weights of the criteria were determined using the AHP method, and the fuel alternatives were ranked according to their sustainability performance using the VIKOR method. The VIKOR method provides compromise solutions by balancing conflicting criteria and enables the selection of the most suitable alternative. This method is applicable in the context of the operational constraints and priorities of the maritime sector, facilitating the determination of sustainable fuel alternatives. The integrated use of AHP and VIKOR methods enables a comprehensive assessment of fuel alternatives considering environmental, economic, and technical dimensions. The hierarchical structure used in this study is presented in Figure 2.

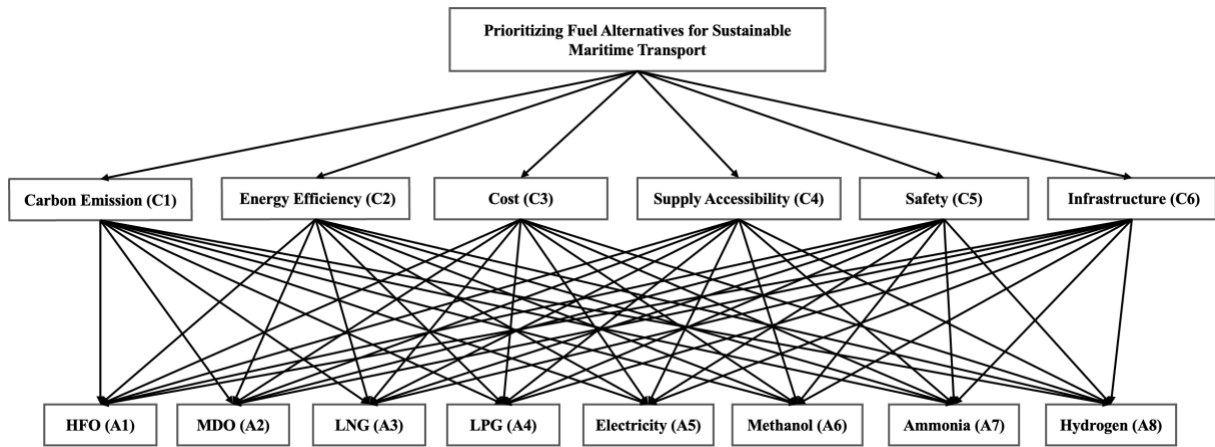


Figure 2 Hierarchical structure

At the highest level of the hierarchical structure, the evaluation of fuel alternatives in terms of sustainability is included, and in this regard, six main criteria have been defined: carbon emission, energy efficiency, cost, supply accessibility, safety, and infrastructure. The criteria in Table 4 allow for a comprehensive assessment of the fuels' environmental, economic, and technical dimensions.

Table 4
Criteria and their explanations

Criteria	Explanations
Carbon Emission (C1)	Carbon emission is considered a key criterion in evaluating fuels in terms of environmental impact and sustainability. International environmental targets and the pursuit of sustainable fuels have made carbon emission a primary consideration in fuel selection (Wang et al., 2023).
Energy Efficiency (C2)	Energy efficiency refers to the capacity to utilize the maximum amount of energy released as a result of the combustion reaction of the fuel type used. Enhancing energy efficiency reduces fuel consumption and costs, while also minimizing negative environmental effects (Tadros et al., 2023). Therefore, energy efficiency is considered a critical factor in evaluating the operational performance of fuel types.
Cost (C3)	Cost is one of the key criteria used to compare different fuel types. This concept encompasses not only the purchase price of the fuel but also expenses related to storage, transportation, usage, and required infrastructure investments (Solakivi et al., 2022).
Supply Accessibility (C4)	Supply accessibility refers to the availability and continuity of fuel supply. It is influenced by factors such as the geographical spread of the fuel, production capacity, storage facilities, and logistics infrastructure (Al-Enazi et al., 2021). Therefore, supply accessibility should be considered as a strategic factor when evaluating both the current availability and long-term sustainability of fuels.
Safety (C5)	Safety refers to the control and prevention of risks associated with fuel storage, transportation, and use. It encompasses characteristics such as flammability, toxicity, leakage, and explosion potential, as well as the precautions required to manage these risks effectively (Zanobetti et al., 2023).
Infrastructure (C6)	Infrastructure encompasses the equipment required for the effective use of fuels, storage facilities, transportation systems, and their integration into ships. It also assesses how easily new fuel types can be incorporated into the existing infrastructure and the extent to which additional infrastructure is required (Wei et al., 2023).

The fuel alternatives presented in Table 5 include traditional fossil fuels (HFO, MDO) as well as alternative fuels targeting low emissions or zero carbon emissions (LNG, LPG, methanol, ammonia, hydrogen, and electricity). These alternatives have been comprehensively evaluated using the VIKOR method in terms of their environmental impacts, economic viability, and technical suitability based on the established criteria. As a result of the analysis, the most suitable fuel alternative for sustainable maritime transport has been determined.

Table 5
Fuel alternatives and their explanations

Fuel Alternatives	Explanations
Heavy Fuel Oil (HFO) (A1)	HFO is one of the leading fuel types in maritime transport. It is produced from crude oil through refining and distillation. Its composition includes high concentrations of sulfur and heavy metals (Ampah et al., 2022). The use of HFO and other fossil-based marine fuels leads to adverse effects on human health and the environment.
Marine Diesel Oil (MDO) (A2)	MDO is a blend of marine gas oil and distilled diesel oils. It contains less sulfur and produces lower emissions than HFO. However, it still causes air pollution and carbon emissions (Mohammadpour & Salehi, 2025).
Liquefied Natural Gas (LNG) (A3)	LNG is a fuel obtained from natural gas. Compared with traditional fossil fuels, LNG produces much lower CO ₂ , NO _x , and particulate matter emissions. However, the feasibility of LNG depends on factors such as storage requirements, infrastructure availability, and safety considerations (Wanying et al., 2025).
Liquefied Petroleum Gas (LPG) (A4)	LPG is a highly energy-efficient fuel that provides environmental advantages due to its low carbon emissions and lack of sulfur. Although it is considered a cleaner alternative for maritime transport, its wider adoption is limited by the need for storage and suitable infrastructure (Yeo et al., 2022).
Electricity (A5)	Electricity is an alternative fuel that is gaining attention in the maritime sector because it supports zero-emission goals. It provides advantages such as high energy efficiency, a low emission profile, and ease of maintenance. However, its widespread adoption is limited by the large battery capacity required for marine operations and the lack of charging infrastructure (Wang et al., 2025).
Methanol (A6)	Methanol is emerging as a promising marine fuel because it offers a cleaner emission profile and remains liquid at ambient conditions, which simplifies storage, handling, and engine retrofitting. However, its adoption is limited by its lower energy density, safety concerns related to toxicity, and the early-stage development of dedicated bunkering infrastructure (Wanying et al., 2025).
Ammonia (A7)	Ammonia is an alternative marine fuel that is carbon-free and produces no CO ₂ emissions during combustion. Its low liquefaction temperature enables storage in liquid form, which facilitates handling and transport on ships. However, its use is constrained by its high toxicity and corrosive characteristics, as well as the need for engine retrofitting and strict safety protocols (Wanying et al., 2025).
Hydrogen (A8)	Hydrogen is an alternative marine fuel with zero carbon content. Despite this advantage, its storage requirements,

Fuel Alternatives	Explanations
	flammability risks, and limited supporting infrastructure make its use in maritime transport challenging (Kaiser & Chowdury, 2025).

To make the decision-making process more objective, four different experts (E1-E4) were asked to provide evaluations. The expert group included two senior marine engineers with operational experience in ship fuel systems, one academic specializing in maritime energy and sustainability, and one project engineer working on alternative fuels. These experts determined the relative importance of the criteria using pairwise comparison matrices. Subsequently, the alternatives were evaluated based on these criteria using the VIKOR method. The pairwise comparison matrices created by the experts are presented in Table 6.

Table 6
Pairwise comparison matrices of criteria according to expert evaluations

CR= 0.0935		E1					CR= 0.0864		E2				
	C1	C2	C3	C4	C5	C6		C1	C2	C3	C4	C5	C6
C1	1	3	1	5	5	5	C1	1	5	1/3	5	3	5
C2	1/3	1	1/3	3	3	3	C2	1/5	1	1/7	1/3	1/3	1
C3	1	3	1	5	3	5	C3	3	7	1	7	5	5
C4	1/5	1/3	1/5	1	1/5	1/3	C4	1/5	3	1/7	1	1/3	1/3
C5	1/5	1/3	1/3	5	1	5	C5	1/3	3	1/5	3	1	3
C6	1/5	1/3	1/5	3	1/5	1	C6	1/5	1	1/5	3	1/3	1
CR= 0.0991		E3					CR= 0.0896		E4				
	C1	C2	C3	C4	C5	C6		C1	C2	C3	C4	C5	C6
C1	1	3	3	5	5	3	C1	1	3	5	1	1	7
C2	1/3	1	1/3	3	1	1/3	C2	1/3	1	1	5	1/3	3
C3	1/3	3	1	3	1/5	1	C3	1/5	1	1	1	1/3	1
C4	1/5	1/3	1/3	1	1/5	1/3	C4	1	1/5	1	1	1/5	1
C5	1/5	3	5	5	1	5	C5	1	3	3	5	1	3
C6	1/3	3	1	3	1/5	1	C6	1/7	1/3	1	1	1/3	1

The arithmetic average of each pairwise comparison matrix presented in Table 5, created by the experts, was calculated, and the resulting matrix was normalized. By normalizing the matrix, the criteria weights were determined and are shown in Figure 3.

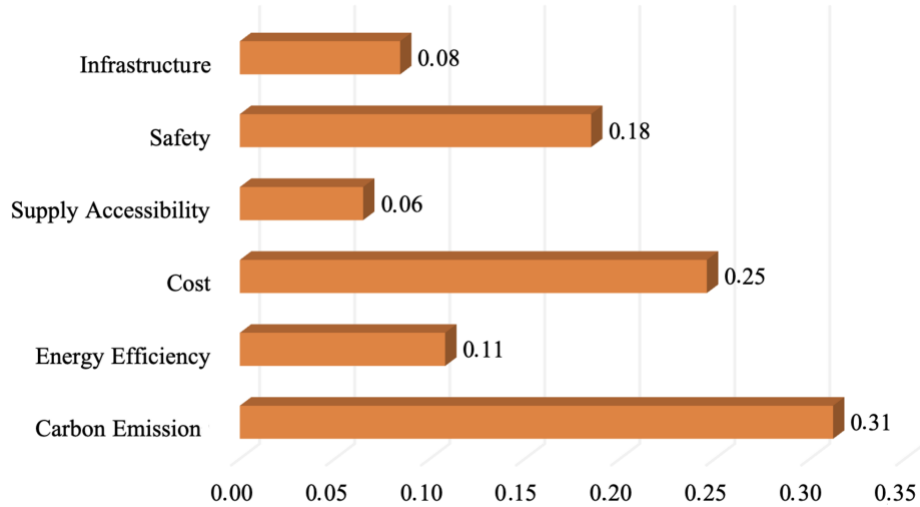


Figure 3 Criteria weights

According to the results presented in Figure 3, carbon emission emerges as the most prioritized criterion with a weight of 31%. This clearly demonstrates the decisive role of environmental impacts in sustainability-focused evaluations. Carbon emission is followed by cost at 25% and safety at 18%. These two criteria indicate the significant impact of economic feasibility and operational risks on fuel preferences. Technical and logistical factors, such as energy efficiency (11%), infrastructure (8%), and supply accessibility (6%), have relatively lower weights. The obtained weights suggest that environmental and economic factors are prioritized over technical aspects. The criteria weights obtained from the AHP method were integrated into the VIKOR method. In the VIKOR method, similar to the AHP, data was collected from four experts (E1-E4). The experts were asked to evaluate fuel types based on the defined criteria. The evaluations from the experts are presented in Table 7.

Table 7
Evaluation of alternatives by experts based on criteria

	E1							E2					
	C1	C2	C3	C4	C5	C6		C1	C2	C3	C4	C5	C6
A1	00	02	08	02	02	00	A1	02	04	10	10	08	10
A2	02	04	04	04	02	02	A2	04	04	08	08	08	10
A3	06	08	10	08	06	08	A3	06	06	08	06	06	08
A4	06	06	08	08	08	08	A4	06	06	06	06	06	08
A5	10	10	04	10	10	10	A5	10	10	04	02	08	04
A6	08	08	06	04	06	06	A6	08	08	02	02	04	02
A7	08	06	04	04	04	02	A7	08	08	02	02	04	02
A8	10	10	06	04	08	04	A8	08	08	00	00	00	00

	E3							E4					
	C1	C2	C3	C4	C5	C6		C1	C2	C3	C4	C5	C6
A1	00	00	08	06	04	08	A1	02	02	08	08	04	08
A2	08	08	08	06	08	08	A2	04	06	06	08	08	08
A3	08	08	08	06	08	08	A3	04	06	08	06	08	08
A4	08	08	08	06	08	08	A4	06	08	06	06	08	08
A5	10	10	04	04	06	04	A5	10	10	04	06	08	02
A6	08	08	04	04	06	06	A6	08	08	06	04	06	06
A7	10	10	08	08	08	08	A7	10	08	08	08	04	04
A8	10	08	04	04	06	06	A8	10	08	02	02	06	02

Table 8
Evaluation of alternatives by all experts based on criteria

	C1	C2	C3	C4	C5	C6
A1	1.0	2.0	8.5	6.5	4.5	6.5
A2	4.5	5.5	6.5	6.5	6.5	7.4
A3	6.0	7.0	8.5	6.5	7.0	6.7
A4	6.5	7.0	7.0	6.5	7.5	6.0
A5	10	10	4.0	5.5	8.0	5.0
A6	8.0	8.0	4.5	3.5	5.5	5.0
A7	9.0	8.0	5.5	5.5	5.0	4.0
A8	9.5	8.5	3.0	2.5	5.0	3.0
f_j^*	10	10	3.0	6.5	8.0	7.4
f_j^-	1.0	2.0	8.5	2.5	4.5	3.0

In Table 8, the best and worst values for each criterion were determined based on the alternatives. Following this step, the mean of group utility S_i and the maximal regret value R_i for each alternative were calculated. Finally, the Q_i index values were obtained, and the alternatives were ranked. The ranking of the alternatives is shown in Figure 4.

Table 9
Ranking of alternatives based on criteria

Si	Rank	Ri	Rank	Qi	Rank
0.868	8	0.310	8	0.750	8
0.485	6	0.189	6	0.382	6
0.487	7	0.240	7	0.432	7
0.392	4	0.174	5	0.307	4
0.107	1	0.049	1	0.000	1
0.391	3	0.135	2	0.269	3
0.418	5	0.162	3	0.313	5
0.350	2	0.162	3	0.268	2

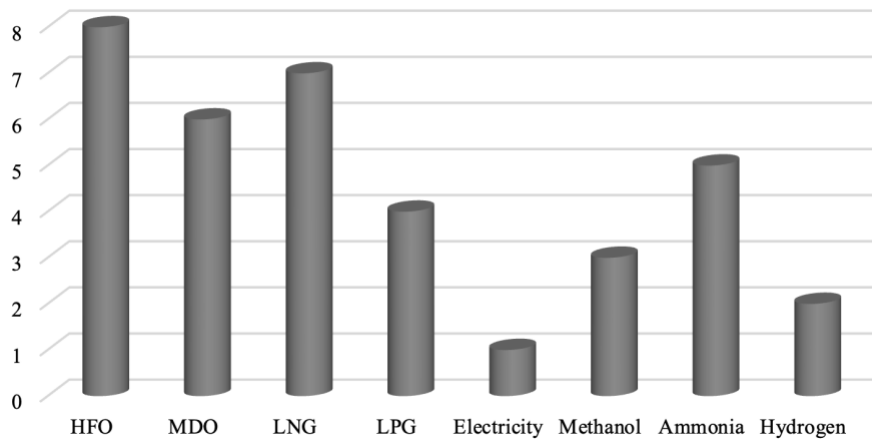


Figure 4 Ranking of alternatives

Based on the results obtained using the VIKOR method, fuel alternatives have been evaluated based on sustainability criteria, with electricity ranking first as the most suitable option. The top ranking of electricity highlights the significance of its advantages, such as zero carbon emissions, high energy efficiency, and integration potential with renewable energy, which play a decisive role in sustainability-focused evaluations. Hydrogen ranks second, attracting attention with its zero carbon emissions and suitability for long-term energy transition. Methanol, ranked third, presents a relatively favorable environmental profile, but its position is lower because its carbon footprint varies depending on production pathways. LPG and ammonia occupy middle ranks, offering certain environmental and operational advantages; however, they fall behind due to technical and economic limitations. Notably, ammonia, despite its zero carbon content, remains in the preparatory stage for widespread application due to its developing technology and safety concerns. MDO and HFO, traditional fossil fuels, are positioned at the lower ranks. This highlights that these fuels are at a disadvantage compared to alternative fuels due to their high carbon emissions, negative environmental impacts, and incompatibility with long-term sustainability goals. Specifically, HFO's position at the bottom of the list signals that it should be phased out from a sustainable maritime perspective. The findings suggest that environmental impacts and technical suitability are decisive factors in fuel selection, while traditional fossil fuels are losing relevance in line with sustainable maritime transport objectives. In this context, increasing the shift towards

clean energy sources such as electricity and hydrogen is considered a critical strategy for transitioning to sustainable maritime transport.

5. Discussion

This study shows that environmental, economic and safety criteria play a decisive role in the evaluation of fuel alternatives in maritime transport. The placement of electricity and hydrogen at the top of the ranking indicates that carbon free fuel types hold a critical role in meeting long term sustainability expectations. Mandić et al. (2021) identified electricity as the most sustainable option among all alternatives. Hansson et al. (2019) demonstrated that hydrogen produced from renewable resources is a strong option in relation to long term climate goals and increasingly demanding environmental regulations. Al-Enazi et al. (2021) indicated that ammonia can contribute positively from an environmental perspective because of its potential to reduce greenhouse gas emissions, yet it also carries important technical limitations related to toxicity and safety risks. The relatively high weight of the safety criterion in this study limited the upward movement of ammonia within the ranking, which is consistent with the risks reported in the literature.

Deniz and Zincir (2016) emphasized that LNG is feasible in terms of cost and infrastructure but does not fully align with long term climate goals because of its fossil-based structure. Ren and Lützen (2017) showed that LNG can perform well in several technical dimensions, yet lower carbon alternatives gain an advantage when climate-oriented criteria are prioritized. The lower ranking of traditional fossil based fuels such as MDO and HFO is consistent with the findings of Al-Enazi et al. (2022). The high carbon intensity of these fuels limits their compatibility with long term sustainability scenarios.

Overall, the findings are consistent with the evaluations presented in the literature. Low carbon fuels stand out with their long term potential, while methanol and LNG emerge as viable medium term options because of their technical and operational characteristics. Hydrogen and ammonia offer strong environmental advantages but remain in a developmental stage due to cost and safety constraints. Fossil fuels show the lowest sustainability performance because of their high carbon intensity.

6. Conclusions

This study provides a comprehensive evaluation of alternative fuels in the maritime sector by considering environmental, economic, and technical aspects of sustainability. The main purpose is to identify sustainable fuel alternatives that can guide the sector's transition toward low carbon operations. The analyses conducted using the integrated AHP and VIKOR methods enabled a systematic weighting of criteria and a consistent ranking of alternatives, providing a transparent decision-making framework for the maritime industry. The findings show that transitioning to innovative fuel types not only offers environmental protection but also enhances operational efficiency and provides long-term economic benefits. Electricity and hydrogen emerged as the most promising alternatives due to their zero carbon emissions, high energy efficiency, and compatibility with renewable energy systems. However, the widespread use of these fuels has not yet reached the desired level due to high investment costs, limited infrastructure, and technical challenges. Methanol and LNG, on the other hand, stand out as transitional options that can be implemented

more easily in the medium term owing to their compatibility with existing infrastructure and relatively lower emissions. Traditional fuels such as MDO and HFO are still preferred in certain areas because of their current economic advantages, although their continued use is incompatible with global decarbonization targets.

From a managerial perspective, the results highlight the importance of supporting clean energy investments, strengthening infrastructure, and developing financial incentives for alternative fuels. The findings also provide strategic insights for policymakers by emphasizing the need for coordinated efforts between governments, ports, and private stakeholders to accelerate the green transition of maritime transport. Moreover, the study contributes to the literature by offering a methodological framework that demonstrates how MCDM methods can be applied in the maritime sector. However, this study has certain limitations. The analyses were conducted based on specific criteria, and although the set of criteria used in the model is broad, aspects such as social impacts, life cycle costs, and political factors were excluded from the scope.

Future research should evaluate fuel alternatives under different operational scenarios, incorporate diverse expert opinions into the analysis, and strengthen the model using data from field applications. Additionally, integrating environmental impact measurement tools such as life cycle analysis and considering the applicability of new technologies will help achieve more holistic results. In conclusion, this study contributes to the green transformation of the maritime sector by addressing the technical requirements, operational challenges, and strategic decisions involved in the transition to sustainable maritime transport. However, for this transformation to succeed, academic research as well as the active involvement of industry representatives and private-sector collaborations must be ensured.

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